PB85-172641

Variability of Short Term Eddy-Correlation Estimates of Mass Exchange

Argonne National Lab., IL

Prepared for

Environmental Protection Agency
Research Triangle Park, NC

Feb 85

U.S. Department of Commerce
National Technical Information Service
NTIS

PB85-172641

EPA/600/D-85/039
February 1985

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by

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Interagency Agreement
DW930060

EPA Project Officer
Jason Ching

ATMOSPHERIC SCIENCES RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NC 27711

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INFORMATION SERVICE
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SPRINGFIELD, VA. 22161

PB85 172641/AS

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA/600/D-85/039		

4. TITLE AND SUBTITLE
VARIABILITY OF SHORT TERM EDDY-CORRELATION ESTIMATES OF MASS EXCHANGE

5. REPORT DATE
February 1985

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
M.L. Wesely and R.L. Hart

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Argonne National Laboratory
9700 South Cass Ave.
Argonne, IL 60439

10. PROGRAM ELEMENT NO.
CCVN1A/03 Task 3055 (FY-85)

11. CONTRACT/GRANT NO.
IAG #930060

12. SPONSORING AGENCY NAME AND ADDRESS
Atmospheric Sciences Research Laboratory -RTP,NC
Office of Research and Development
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

13. TYPE OF REPORT AND PERIOD COVERED

14. SPONSORING AGENCY CODE
EPA/600/09

15. SUPPLEMENTARY NOTES

16. ABSTRACT

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17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
RELEASE TO PUBLIC	UNCLASSIFIED	25
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

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ABSTRACT

The signals from sensors used to measure atmospheric scalar fluctuations ordinarily produce characteristic spectra and cospectra with vertical wind velocity that are strongly influenced by vertical transport processes. Unwanted signal noise generated by some of the fast response chemical sensors, however, distort the spectra and cospectra and increase run-to-run variability of eddy-correlation flux estimates. Instead of data collection periods of only 30 min needed to provide a precision of approximately 10-20% in each flux estimate obtained at heights of 5-10 m during ideal daytime conditions, an ensemble derived from several such runs is necessary with certain sensors in order to achieve comparable precision. This has been the practical experience obtained in numerous experiments above various natural surfaces, and is verified to a limited extent by both empirical and theoretical investigations.

INTRODUCTION

Estimates of the vertical fluxes of water vapor, heat, and momentum obtained by eddy correlation are subject to run-to-run variability of at least 10% for 30 min data-collection periods at heights of 5-10 m in ideal environmental conditions (Dyer and Hicks, 1972; Wyngaard, 1973). However, the effects of nonstationary atmospheric flow, changing surface conditions, or a nonuniform surface can substantially increase this variability. Further, for sensors recently developed to measure the rapid fluctuations of species such as sulfur and nitrogen

oxides that are present in ambient conditions at very low concentrations, the signal-to-noise ratio is often small and this seems to increase variability also. Here, a statistical approach will be used to examine the imprecision caused by "noisy" sensors.

SOME OBSERVATIONS OF TURBULENCE PROPERTIES

Covariances

The mass flux or, more precisely, the mass flux density, F_c, of a substance of concentration c is calculated by eddy correlation as the covariance

$$F_c = \overline{w'c'}, \qquad (1)$$

where w is the vertical wind velocity, the overbar indicates a time average, and the primes indicate deviations from time averaged quantities. At heights within 10 m of a very large, horizontal flat surface and in ideal conditions including fully turbulent, stationary, horizontally homogeneous flow, the fluxes measured are usually within 1% of those occurring much closer to the bulk surface. Practical experience has shown that averaging times in ideal conditions should be at least 10 min in order to obtain acceptably small variability in fluxes measured at heights of 5-10 m. Longer averaging times are preferable, but are usually limited to 1 h to avoid the effects of natural, slow environmental trends, including nonstationary flow and changes in surface properties associated, for example, with diurnal variations of physiological processes in surface vegetation. Hence, for practical reasons, 30 min samples are often taken.

There are many considerations on the practical limitations of the eddy-correlation technique. It is a sophisticated method not well suited for routine operational measurement of fluxes. Even in ideal conditions, adjustments for tilt of the w sensor and for the effects of fluctuations in air density and water vapor Stefan flow at the surface can be necessary in certain circumstances (Webb et al., 1980; Wesely et al., 1981).

Typical measurements of fluxes or covariances are given in Table 1. Single numbers for each averaging period are given for wind stress, $\tau = \overline{u'w'}$; expressed as friction velocity, $u_* = (-\tau/\rho)^{-1/2}$; sensible heat flux, $H = \rho c_p \overline{w'T'}$; latent heat flux, $\Lambda E = \Lambda \overline{w'Q'}$; and various mass fluxes, $F_c = \overline{w'c'}$. (The term ρ represents air density: u, horizontal wind velocity: w, vertical wind velocity; c_p, specific heat of air at constant pressure; T, air temperature; Λ, the latent heat of vaporization; Q, absolute humidity; and c, trace substance concentration.) For the examples in Table 1, the fluxes F_c are for ozone (F_O), nitrogen compounds (NO_x, F_N), and a quantity υ

Table 1. Half hour averages of fluxes and standard deviations measured in Lancaster Co., PA, on 16 August, 1979, above soybeans, centered on the times shown.

Time Center CST	u_* cm s^{-1}	σ_w cm s^{-1}	H W m^{-2}	λE W m^{-2}	O_3 F_O ppb cm s^{-1}	O_3 σ_O ppb	NO_x F_N ppb cm s^{-1}	NO_x σ_N ppb	U F_U mV cm s^{-1}	U σ_U mV
0915	39	42	69	311	-22.4	1.53	-	-	-33.2	7.8
0945	44	39	68	312	-22.6	1.55	-	-	-61.1	9.6
1015	42	39	73	363	-27.1	1.67	-4.4	2.00	-58.3	9.3
1045	40	42	92	411	-30.6	1.83	-3.3	2.13	-48.9	9.4
1115	38	42	82	428	-31.8	2.09	-6.4	2.05	-69.6	11.3
1145	39	39	87	423	-31.1	1.98	-4.1	2.01	4.5	8.3
1215	39	40	80	474	-37.7	2.28	-4.4	2.00	-23.9	11.5
1245	38	40	59	396	-32.0	2.19	-4.0	1.95	-38.4	10.2
1315	25	36	71	440	-36.8	2.33	-1.5	1.88	5.4	8.8
1345	28	33	54	393	-32.2	2.32	-4.0	1.86	-	-
1415	45	42	88	574	-50.4	2.44	-2.9	1.92	-6.8	15.8
1445	31	30	-6	257	-26.2	2.80	-1.8	1.86	-30.3	23.6
1515	35	33	39	401	-35.4	2.21	-2.3	2.19	-25.0	16.0

(F_U) for an improperly positioned particle sensor. The nitrogen compounds are NO_x = NO + NO_2 + HNO_3 plus possibly other species and the particles were sensed by a nephelometer several meters away from the w sensor, too far for proper flux measurement. These flux data were obtained at a height of 5.2 m over a field of lush soybeans during an experiment described fully elsewhere (Wesely et al., 1982; Eastman, 1983; Wesely and Stedman, 1983). The flux estimates were actually computed for 25 min of each half hour by use of a digital computer. An alternate computational procedure is to use analog electronic covariance meters; this was accomplished with an analog system consisting of components similar to those described by Hicks (1972). Figure 1 shows traces obtained from strip chart records of electronic signals from a six channel covariance meter supplied with inputs of w, u, T, Q, O_3, and υ, operated in parallel with the digital computer. These are smoothed traces because the covariance meter treats the flux signals with a low pass, active, single pole, electronic filter with a cutoff time constant of approximately 1000 s.

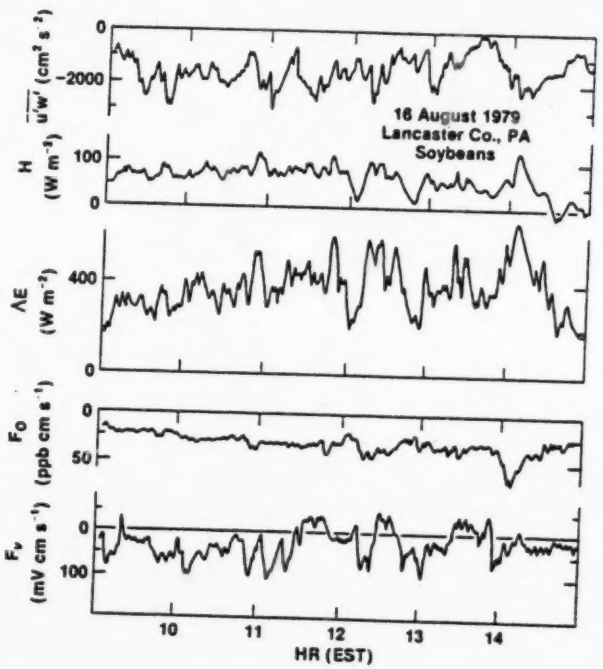

Figure 1. Traces of flux signals derived from an analog covariance meter, operated in parallel with a digital computer that produced the flux estimates given in Table 1.

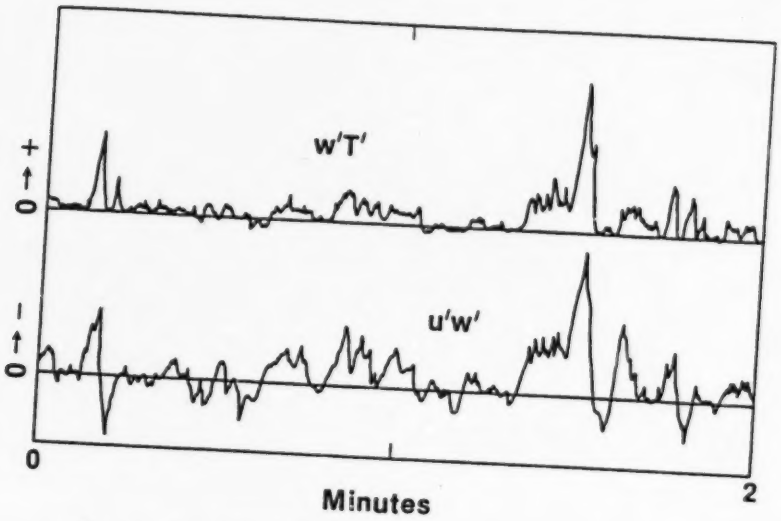

Figure 2. Examples of flux signals obtained 5 m above a grassy field during slightly unstable conditions, prior to significant averaging.

The actual extent of the temporal variation in vertical fluxes can be seen in the product signal prior to averaging by the analog covariance meter. Figure 2 shows a set of such signals. Similar traces can be produced by appropriate calculations with a digital computer. Evidently, the vertical transfer processes are characterized by a great deal of variability. As is typical for the slightly unstable conditions present when the data shown in Figure 2 were collected, some intermittency in the upward heat flux is present. As illustrated by Figures 1 and 2, a reasonable estimate of the time scales for most of the atmospheric variability of instantaneous turbulent flux seems to be approximately 1 s to 10 min (for wind speeds of 3-6 m s^{-1} at heights of 5-6 m above a moderately rough surface during unstable atmospheric conditions). Thus we should expect that a 25 min averaging time is sufficient for a fairly good estimate of an eddy flux. At the high frequency end, fluctuations occurring more than once a second are strongly attenuated in Figure 2 due to the response characteristics of sensors (which included a propeller anemometer for w, a fast response cup anemometer for u and a bead thermister for T), but it generally accepted that such fast fluctuations are unimportant in carrying fluxes in these conditions. To specify more clearly the frequency range of greatest importance, spectra and cospectra of fluctuations can be examined.

Spectra and Cospectra

Many researchers have investigated the spectral and cospectral properties of turbulent flow in the atmosphere. For example, Kaimal et al. (1972), Kaimal (1973), and Høstrup (1981) provide averaged normalized plots of spectra of u, w, and T, and cospectra of uw and wT. Somewhat universal shapes of the spectra are obtained as a function of normalized frequency $f = nz/\bar{u}$ where n is the cyclical frequency, z is the height above the surface, and $\bar{u}$ is the average local wind speed. Variations in shape, usually associated with greater low frequency contributions as the atmosphere becomes less stable, are noted or parameterized. The purposes of presenting spectra and cospectra here are mainly to check the performance of our data collection methods and to identify some of the characteristics of some of the sensors used.

Figure 3 shows a sample of spectra of w and Q obtained for the 25 min period centered at 1515 h on 16 August, at the Lancaster site, corresponding to one of the lines in Table 1. The Q spectra indicates that the Lyman-alpha hygrometer seems to have performed quite well, since the -5/3 slope (-2/3 on the plots as configured with nS(n) on the vertical axis) characteristic of the inertial subrange is achieved to nearly

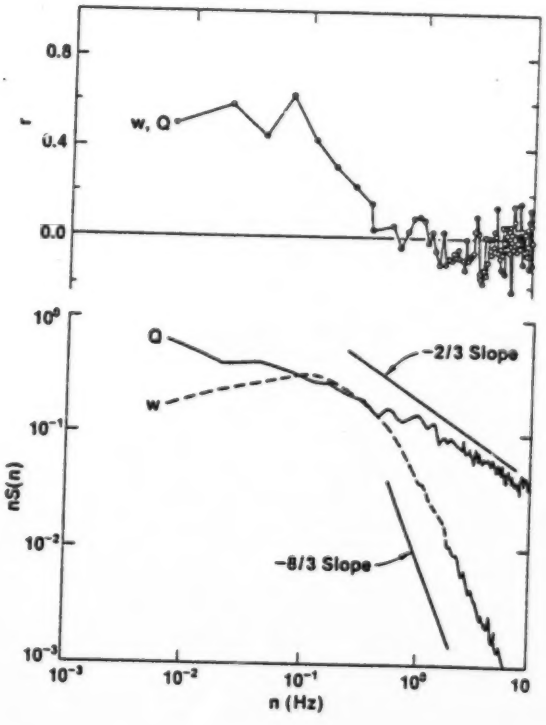

Figure 3. Spectra of vertical wind velocity and water vapor density on an arbitrarily scaled vertical axis (lower) and their spectral correlation coefficient (upper) for 1515 EST on 16 August 1979 at the Lancaster site.

10 Hz without difficulty. As is well known (e.g., see Lumley and Panofsky, 1964), the influence of flux carrying eddies in the atmospheric surface layer on spectral shapes of such turbulence signals diminishes rapidly beyond f = 1, allowing the inertial subrange to form, with its characteristic slope that extends to the much higher frequencies where molecular dissipation of fluctuations takes place. Fluctuations of w measured with the propeller, however, are strongly attenuated at frequencies greater than 1 Hz. On the basis of a response length of approximately 2 m (Hicks, 1972) likely at the average wind speed of 3.5 m s^{-1} present during the 25 min sample period, the propeller has an exponential response time of 0.6 s. This is consistent with the severe attenuation at the high frequencies and a rolloff slope of approximately -8/3 as shown in Figure 3. The -8/3 slope results from a convolution of the atmospheric inertial subrange signal with the filter function $[1 - (2\pi n\imath)^2]^{-1}$, which alone produces a slope of -2 where $\imath$ is the exponential response time of the sensor. While the flux estimates in Table 1 (and elsewhere in this paper when a propeller anemometer is used) have been adjusted to compensate for this poor frequency response (Wesely, 1983), none of the cospectral plots have been adjusted. Hence, cospectra as well as spectra involving w from the propeller anemometer will be severely attenuated beyond $n = \bar{u}/\ell$, where ℓ = 2 m is the response length of the instrument, for most conditions over land surfaces. This attenuation is evident in the upper portion of Figure 3, which shows the spectral correlation coefficient,

$$r_{wQ} = C_{wQ}(n)[S_w(n)S_Q(n)]^{-1/2} \qquad (2)$$

where $C_{wQ}(n)$ is the cospectrum and $S_w(n)$ and $S_Q(n)$ are the spectra.

Normally, it is expected that flux carrying eddies dominate spectra at normalized frequencies $f = nz/\bar{u}$ near 0.1 and diminsh rapidly in influence beyond f = 1. For Figure 3, with wind speed of $\bar{u}$ = 3.5 m s^{-1} and a height of z = 5.2 m, the upper limit of the frequency for strong flux carrying eddies is near $n = \bar{u}/z$ = 0.7 Hz. The upper limit actually evident in Figure 3 appears to be slightly smaller.

Figure 4 shows the spectral characteristics of the output from the O_3 sensor, which utilizes a gas phase chemiluminescent reaction between ambient ozone and nitric oxide (Eastman and Stedman, 1977; Eastman, 1983), along with spectra from the NO_x sensor, which converts ambient NO_x species to NO and detects light emitted by a chemiluminescent reaction between NO and excess O_3 supplied to the sensor (Stedman et al., 1972; Wesely et al., 1982). These sensors have similar characteristics, as would be expected on the basis of their design and principles of operation. Both are subject to thermal noise that appears as "white" noise at the high frequencies in Figure 4. A slope

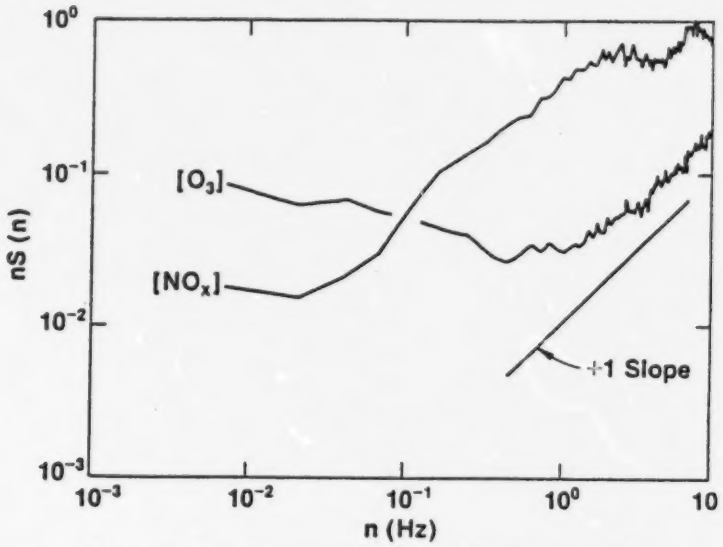

Figure 4. Spectra of O_3 and NO_x turbulent fluctuations for the same period and site as in Figure 3, plotted with an arbitrarily scaled vertical axis, different for each chemical species.

of +1, typical of white noise in a log-log plot of nS(n) versus n, is seen for n > 1 Hz for the O_3 sensor and n > 0.1 Hz for the NO_x sensor. Unfortunately, the limitations of the two chemiluminescent sensors with regard to speed of response are hidden in Figure 4 by the thermal noise. The earlier appearance of the noise in the NO_x spectrum indicates a smaller signal-to-noise ratio and is probably associated with the ambient concentrations of NO_x being nearly 10 times smaller than the O_3 concentrations, 5.3 ppb versus 46 ppb, and with the turbulent transfer rate for NO_x being slightly smaller than for O_3 (Wesely et al., 1982). Also, since laboratory tests have shown that the amplitude of the thermal noise in each sensor increases as the signal levels or ambient concentrations increase, the NO_x sensor seems to be intrinsically more noisy than the O_3 sensor.

Laboratory measurements have shown that characteristic exponential response times are 0.3 s for the O_3 sensor and 0.15 s for the NO_x sensor. Furthermore, the delay times required for the sample air to travel from near the measurement point (near the w sensor) and down the sample tube to the reaction chambers are not known more accurately than 0.05 s, so the digital correction for this time-series mismatch might be slightly inaccurate. This, together with sampling locations being separated by as much as 0.7 m, undoubtedly contributes to

the rolloff at high frequencies as in Figure 5. The data for these plots were collected at the same Lancaster site during the daytime on August 15, when conditions were nearly the same as for the daytime of August 16 considered in the previous plots, except that the wind speed was considerably greater, near 6.1 m s^{-1}. A similar rolloff for r_{QT} is seen, undoubtedly influenced also by the response time 0.12 s of the temperature sensor and its physical separation of 0.6 m from the humidity sensor, which is considerably faster in response. Hence, we should not consider the rapid rolloff at frequencies near n = 1 Hz as being necessarily indicative of true atmospheric behavior, but probably a result of experimental limitations.

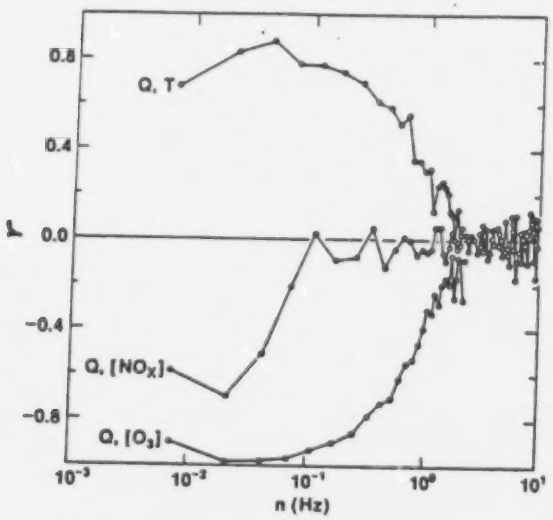

Figure 5. Spectral correlation coefficients of water vapor density with temperature, NO_x and O_3 for 1345 EST on 15 August, 1979, at the Lancaster site.

There are two major points to made with Figure 5. One is that the high degree of correlation evident between the scalar quantities indicates a similarity of transfer mechanisms, as discussed by Wesely (1983). This similarity seemingly does not extend to NO_x species, but such a conclusion might be invalidated by the relatively great noisiness of the NO_x sensor, especially at the higher frequencies as discussed above in relation to Figure 4. The second point is that noise might distort cospectra between such chemical concentration signals and Q and perhaps w signals, and that this probably increases the run-to-run variability of the flux estimates obtained by eddy correlation. Indeed, the eddy flux estimates can be considered as integrals of the cospectra between w and the chemical species measured. There is some inkling of significantly greater run-to-run variability of the NO_x fluxes than for the O_3 fluxes listed in Table 1: the standard deviation of the NO_x fluxes listed for between 0900 and 1500 h are 35-40% of the mean value, but for O_3 are 20-25% despite a greater

temporal trend in the mean concentrations of O_3 (Wesely et al., 1982). This difference could be interpreted as the result of different transfer processes for NO_x and O_3, but is probably an artifact of the noisy NO_x sensor. In the following section we examine theoretically the natural variability of eddy-correlation flux signals and the variability caused by sensor noise.

THEORY

Review

Lumley and Panofsky (1964) show that the averaging time, T, required to obtain an "accuracy" a in the estimate of the mean of a turbulent quantity, ξ, can be expressed in terms of an integral time scale, τ, and the long term variance, σ_ξ^2:

$$T = 2\tau\sigma_\xi^2(a\bar{\xi})^{-2}. \tag{3}$$

The intent here is to consider ξ to be an instantaneous flux product w'c', where c is the scalar concentration. We utilize the ergodic hypothesis in order to utilize one or a series of time averages in place of a true ensemble average. We further assume that the flow is stationary and that no substantial change occurs in atmospheric or surface conditions that would change $\bar{\xi}$ or σ_ξ. Wyngaard (1973) has utilized this expression to estimate averaging times necessary with ideal conditions and sensors to achieve specified accuracies for a number of turbulence quantities, including the covariances $\overline{u'w'}$ and $\overline{w'T'}$. The integral time scale is assumed proportional to $z/\bar{u}$, based on theoretical considerations, and this corresponds roughly with the inference, made from analysis of cospectra between w and scalar quantities, that the flux carrying eddies contribute little beyond frequencies of $n = \bar{u}/z$.

Wyngaard (1973) finds that the averaging time necessary to achieve a value of a in heat flux estimates is

$$T = z(a^2\bar{u})^{-1}[\sigma^2_{w'T'}(u_*^2T_*^2)^{-1} - 1], \tag{4}$$

where $T_* = -\overline{w'T'}/u_*$. For near neutral conditions, the well known Kansas data indicate that T is

$$T = 20z(a^2\bar{u})^{-1}, \tag{5a}$$

and for unstable conditions is

$$T = 12z(a^2\bar{u})^{-1}. \tag{5b}$$

Hence, to achieve a value of a = 0.10 with the conditions corresponding to the time and location considered in Table 1 ($z = 5.2$ m, $\bar{u} \simeq 4$ m s^{-1}, unstable conditions), an averaging time of nearly 30 min is needed, a very reasonable expectation based on discussions earlier in this paper and the observations of Dyer and Hicks (1972). This result is easily generalized to fluxes of other scalar quantities if, as suggested above in reference to Figure 5, the spectral correlation coefficient is near unity at frequencies where the flux-carrying eddies are found. The effects of noisy sensors, however, is a matter not normally considered in the micrometeorological scientific literature.

Analysis Based on Variances

An alternative to Wyngaard's (1973) approach of using normalizing factors such as u_* and $c_* = -\overline{w'c'}/u_*$ in Equation (4) is to rederive basic expressions based on slightly different second order statistics. This permits examination of the effects of sensor noise. Some definitions and explanations are needed first. The standard error in determining the mean value of a property, ξ, in a stationary time series is the standard deviation divided by the square root of the number m of (independent) samples:

$$\sigma_{\bar{\xi}} = \sigma_{\xi} m^{-1/2}, \tag{6}$$

where σ_{ξ} is determined over a time interval that is large compared to the associated integral time scale. For a finite time series corresponding to a real span of time, the number m (approximately the number of degrees of freedom) can be varied, for example, by choosing a shortened time series that is a subset of the total dataset or by varying the total number of equally spaced discrete samples and, thus, effectively changing the sampling interval in the total dataset. For a given number of estimates of $\bar{\xi} = \overline{w'c'}$, each obtained from m samples of ξ over a specified time interval, $\sigma_{\bar{\xi}} = \sigma_{\overline{w'c'}}$ is the standard deviation of the mean flux estimates. This is the measure of run-to-run variability we are seeking. Further, $\sigma_{\overline{w'c'}}/F_c$ is the "accuracy" a as specified by Lumley and Panofsky (1964) and Wyngaard (1973), where F_c is the true flux or grand mean average of $\overline{w'c'}$. We will refer to a as the "precision".

The quantity $\sigma_{\bar{\xi}}^2$ here is actually

$$\sigma_{\overline{w'c'}}^2 = \overline{(w'c')'^2} = \overline{(w'c' - \overline{w'c'})^2}. \tag{7a}$$

By use of standard Reynolds averaging procedures and the expansion

$$\overline{(w'c')^2} = \overline{w'^2}\ \overline{c'^2} + \overline{(w'^2)'(c'^2)'}, \tag{7b}$$

it can be shown that

$$\sigma^2_{w'c'} = \overline{w'^2}\ \overline{c'^2}(1 - R^2_{wc}) + \overline{(w'^2)'(c'^2)'}, \qquad (7c)$$

where $R_{wc} = \overline{w'c'}(\overline{w'^2}\ \overline{c'^2})^{-1/2}$ is the correlation coefficient.

Consider the case of a very noisy signal s equal to the sum of the c signal and a noise contribution χ. The value of R_{ws} should be very small and, with little correlation of the noise component with w, it is likely that $\overline{(w'^2)'(s'^2)'}$ also should be small relative to $\overline{w'^2}\ \overline{s'^2}$. Then, Equation (7c) becomes

$$\sigma_{w's'} \simeq \sigma_w \sigma_s, \qquad (8)$$

where σ_w and σ_s have been used to specify $\overline{w'^2}^{1/2}$ and $\overline{s'^2}^{1/2}$, respectively, and the run-to-run variability is expressed as

$$\sigma_{\overline{w's'}} = \sigma_w \sigma_s m^{-1/2}. \qquad (9)$$

If the noise in s is purely white noise and c = 0, then Equation (9) should be fairly accurate if the white noise extends to at least the Nyquist frequency, which is one half the sampling rate or m/(2T). On the other hand, if the fluctuations of both w and s are very small at frequencies above a certain frequency n*, then m is effectively limited to

$$m^* = Tn^*, \qquad (10)$$

where n* can have any value up to m/T. As suggested in the previous section of this paper, n* is typically near $\overline{u}/z$ in the ideal situation of atmospheric fluctuation signals without excess noise generated by sensors. In this case $(n^*)^{-1}$ is approximately equal to the integral time scale τ (or perhaps 2τ) expressed in Equation (3).

A reviewer of this paper and Dr. Leif Christensen (personal communication) of Risø National Laboratory recently have shown that a rigorous derivation of the effects of noise on $\sigma_{\overline{w's'}}$ can be obtained by considering the original basis for Equation (3):

$$\sigma^2_{\overline{\xi}} = \frac{2\sigma^2_\xi}{T} \int_o^\infty \rho_\xi(t)dt, \qquad (11)$$

where ρ_ξ is the dimensionless correlation coefficient

$$\rho_\xi(t) = \frac{2}{\sigma^2_\xi} \int_o^\infty \cos(\omega t) S_\xi(\omega) d\omega, \qquad (12)$$

and S_ξ is the power spectrum of ξ. The integral of Equation (11) yields Equation (3). If ξ consists of two additive parts x and y, integration leads to

$$\sigma_\xi^2 = \frac{2}{T}\sigma_x^2\tau_x + \frac{2}{T}\sigma_y^2\tau_y. \qquad (13)$$

In the case of white noise with a band limit of $\omega = 2\pi n^*$, it can be shown that the integral time scale for y is

$$\tau_y = 1/(2n^*), \qquad (14)$$

and therefore that Equation (13) can be expressed as

$$\sigma_\xi^2 = \frac{2}{T}\sigma_x^2\tau_x + \frac{\sigma_y^2}{n^*T}. \qquad (15)$$

If we evaluate terms as $\xi = \overline{w's'}$, $x = \overline{w'c'}$, and $y = \overline{w'\chi'}$, then we have shown that noise contributions add directly as variances. If χ is much greater than c, then Equation (9) follows directly from (15).

Let us return to the case of ideal sensors deployed in the surface layer, and compare the Reynolds statistics result expressed by Equation (7c) with the earlier formulation given by Equation (5). In Equation (7c), R_{wc} for scalar quantities has values ranging from 0.3 to 0.5 (Busch, 1973; Hicks, 1981). The value of $\overline{(w'^2)'(c'^2)'}$ is probably small in near neutral conditions, although this cannot be stated with certainty. For the time being, we assume that $\overline{(w'^2)'(c'^2)'}$ is equal to $b^2\sigma_w^2\sigma_c^2$ where b is a numerical coefficient possibly dependent on local atmospheric stability. Here it is assumed that $\overline{(w'^2)'(c'^2)'}$ is always positive because, for typical atmospheric fluctuations, increased rapid fluctuations in c are usually accompanied by increased variations in w. The lower limit for b is zero, when w and c are uncorrelated in any sense, and it can be shown that the upper limit for b is probably near 4, when w and c are highly correlated. These considerations, together with the relation $n^* = \bar{u}/z$ and Equation (10) substituted into Equation (9) result in:

$$a = \overline{w'c'}F_c^{-1} = (1 - R_{wc}^2 + b^2)^{1/2}\sigma_w\sigma_c(\bar{u}/z)^{-1/2}/F_c, \qquad (16a)$$

and

$$T = (1 - R_{wc}^2 + b^2)z(a^2\bar{u})^{-1}\sigma_s^2\sigma_c^2/F_c^2. \qquad (16b)$$

Consider the near neutral case when typical values are $R_{wc} = 0.3$, $\sigma_w = 2u_*$, and $\sigma_c = 2F_c/u_*$ (Busch, 1973; Hicks, 1981). If b is assumed equal to one, then T is

$$T = 25z(a^2\bar{u})^{-1}. \qquad (17a)$$

This agrees very well with Equation (5a), but cannot be considered an independent evaluation because of the arbitrary choice of the value of b. For the unstable case, typical values are $R_{wc} = 0.5$, $\sigma_w = 2u_*$, and $\sigma_c = F_c/u_*$. Again, if b is assumed equal to one, good agreement with Equation (5b) is found:

$$T = 12z(\bar{u})^{-1}. \qquad (17b)$$

These comparisons between Equations (5) and (17) indicate agreement between the two approaches that is only tentative because there is substantial uncertainty in the numerical coefficients involved, in both cases.

Neither the expressions given by Equations (9) and (10) nor by Equation (17) address our ultimate goal of considering noise plus real atmospheric signal both contributing to a signal simultaneously. To do so, we resort to an empirical analysis, aided by the implications of Equation (13).

EMPIRICAL EVALUATION OF VARIABILITY

An estimate of run-to-run variability expressed as the standard deviation of flux estimates has been obtained by repeated application of a random noise source to the signal from a sensor with nearly ideal characteristics. With χ representing discrete white noise produced with a random noise generator, $\overline{w'\chi'}$ was calculated for 25 min runs sampled at a rate of $m/T = 17\ s^{-1}$, in accordance with the sampling procedures

Table 2. Conditions associated with the three datasets used to evaluate run-to-run variability of covariances, based on 25 min of data taken for each case.

Case number:	1	2	3
Date	25 June 1982	5 February	9 June 1983
Time (center)	1145 CST	1115 EST	1915 CST
Location	Illinois	Pennsylvania	Oklahoma
Surface	grass	bare soil	grass
Type of w Sensor	propeller	sonic	sonic
Sensor Height (m)	5.7	8	5.5
$\bar{u}$ (m s^{-1})	3.2	2.7	5.1
u_* (cm s^{-1})	28	18	37
z/L	-0.5	-0.8	0.03
raw $\overline{w'Q'}$ (V^2)	0.25	0.10	0.05
raw σ_w (V)	0.72	0.45	0.60
raw σ_Q (V)	0.52	0.19	0.07

employed in recent years during turbulence and flux measurements by Argonne National Laboratory. Three 25 min samples of raw data described in Table 2 were used for these numerical experiments. These are from data collection periods representative of cases from experiments in which hundreds of such 25 min periods of data were collected at each of the field experiment sites. White noise as shown in Figure 6, and filtered such as shown to produce altered noise spectra, was used with each raw time series of vertical wind signal recorded on magnetic tape. For each of the three cases, 1000 repititions were performed in order to obtain a sufficient number of ensemble members for statistical analysis.

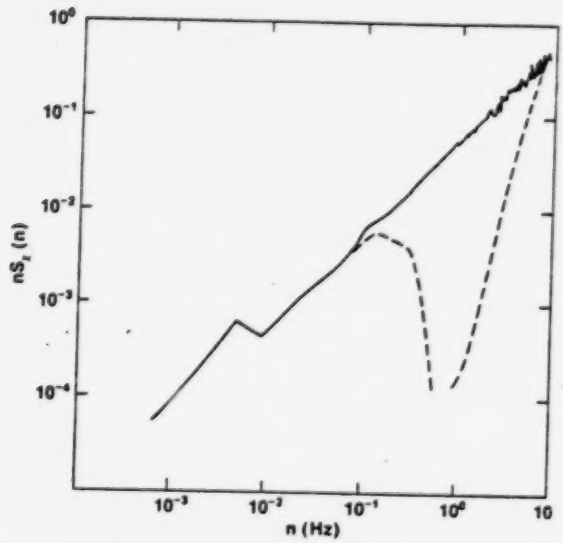

Figure 6. Spectral plot of white noise used to generate the statistics shown in Table 3. The dashed lines indicate the effects of lowpass filtering at 0.212 Hz and high pass filtering at 4.25 Hz.

If we choose to use c as an ideal concentration signal and use $s = c + \chi$ as the contaminated signal, the following are valid:

$$\overline{w's'} = \overline{w'c'} + \overline{w'\chi'} \tag{18}$$

and

$$\sigma^2_{\overline{w's'}} = \sigma^2_{\overline{w'c'}} + \sigma^2_{\overline{w'\chi'}}. \tag{19}$$

Equation (18) follows from standard Reynolds averaging procedures, as does Equation (19), which is also verified via Equation (13). Since χ represents random noise, the ensemble average $\langle\overline{w'\chi'}\rangle$ (or a very long time average of $\overline{w'\chi'}$) is zero, and $\langle\overline{w's'}\rangle$ becomes equal to $\langle\overline{w'c'}\rangle$. This and Equations (18)

and (19) have been verified empirically for the three cases described in Table 2.

The primary statistical results on the effects of white noise are summarized in Table 3. With the different sensors used and the various atmospheric conditions encountered, all three cases indicate that the standard deviation is

$$\sigma_{\overline{w'\chi'}} = 0.0063\sigma_w\sigma_\chi \qquad (20)$$

when unfiltered random noise is applied. The numerical coefficient 0.0063 is equal to $m^{-1/2}$, as predicted earlier by Equations (9) and (15), where n* is equal to the sampling frequency $m/T = 17\ s^{-1}$.

Real sensors rarely have noise that can be described as purely white, i.e., with equal strength of fluctuations at all frequencies sampled. Even for the O_3 and NO_x sensors with spectra as shown in Figure 4, it is not clear that the noise can be characterized as being white at the low frequencies. Two cases where the spectra are contaminated in a manner even more obscure are shown in Figure 7. The data for this figure are from two flame-photometric sulfur sensors sampling the ambient atmosphere during eddy-correlation studies over a grass surface

Table 3. Results of calculations of the effects of random noise on covariances with vertical wind speed for the three cases listed in Table 2, with 1000 ensemble members for each value of $\sigma_{\overline{w'x'}}$. The filtering noted applies only to χ, not w.

Case number:	1	2	3
Full bandwith (σ_x = 2.89 V)			
$\sigma_{\overline{w'\chi'}}$ (V^2):	0.0130	0.0082	0.0113
$\sigma_{\overline{w'\chi'}}$ $(\sigma_w\sigma_\chi)^{-1}$:	0.0062	0.0063	0.0065
High pass (σ_x = 0.65 V, 3 db at 1.7 Hz)			
$\sigma_{\overline{w'\chi'}}$ (V^2):	~0	~0	0.0061
Low pass (σ_x = 1.57 V, 4db at 1.7 Hz)			
$\sigma_{\overline{w'\chi'}}$ (V^2):	0.0130	0.0080	0.0095
$\sigma_{\overline{w'\chi'}}$ $(\sigma_w\sigma_\chi)^{-1}$:	0.0117	0.0112	0.0102

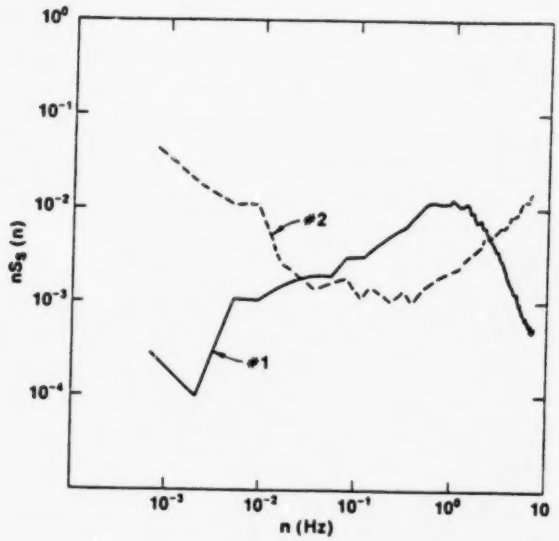

Figure 7. Spectral plots of signals produced by the two particulate sulfur sensors for data corresponding to Case 1 of Tables 2 and 3. While the basic unit for the vertical axis is volts, the two sensors have different sensitivities with respect to sulfur concentration.

during the 1982 Dry Deposition Intercomparison Experiment (DDIE), specifically at the same site and time interval as for Case 1 in Table 2. A denuder tube was used on the inlets of the sensors to strip out gaseous sulfur so that only particulate sulfur was sampled. Sensor #2 had enhanced sensitivity due to adding SF_6 in the hydrogen that fed the flame in the burner chamber and had a signal-to-noise ratio superior to sensor #1, which used unmodified hydrogen. The rolloff beyond n = 1 Hz for sensor #1 is due to electronic filtering. The high level of noise present between n = 0.1 and 1.0 Hz for sensor #1 resulted in standard deviations of measured sulfur concentration fluctuations that were typically 3 times greater than for sensor #2.

Results shown in Table 3 for white noise limited in amplitude at the high frequencies indicate that high frequency sensor noise can contribute very little to $\sigma_{\overline{w'\chi'}}$, commensurate with the fact that the fluctuations in w are relatively small at the high frequencies. Further, the extent of contributions from the high frequencies depends on $\bar{u}$ and atmospheric stability. As in Case 3, strong winds and stable stratification reduce the

time scales of turbulence and thus enhance variability due to high frequency noise. The usual situation for noisy sensors seem to be that the noise amplitude at the lower frequencies is larger than expected on the basis of extrapolation of high frequency noise with an assumption of white noise. As a result, the value of m* becomes smaller than m in Equations (6) and (9).

The sets of data from Table 1 and from a collection of 18 runs of 25 min duration collected at DDIE have been analyzed to produce estimates of precision a and associated variables for mass flux measurements obtained with selected sensors. Results are shown in Table 4. (The spectra in Figures 3-5 and 7 were

Table 4. Summary of statistics on variability of mass flux measurements for the data from Table 1 (upper) and for 25 and 27 June, 1982, including Case 1 of Table 2 (lower).

		total			noise		
	c	$\lvert a \rvert$	f*	σ_d cm s^{-1}	$\lvert a \rvert$	f*	σ_d cm s^{-1}
13 runs, from Table 1, $\bar{u}$ = 3.74 m s^{-1}, z = 5.2 m, z/L ≈ -0.1							
Q:	13 g m^{-3}	0.20	0.09	-	-	-	-
O_3:	38 ppb	0.23	0.11	0.09	0.11	0.15	0.09
NO_x	6.8 ppb	0.39	2.7	0.21	0.34	3.6	0.18
υ	4.3 mV	0.77	0.31	5.7	0.75	0.32	5.5
18 runs, from DDIE, $\bar{u}$ = 3.66 m s^{-1}, z = 5.7 m, z/L ≈ -0.5							
Q:	14 g m^{-3}	0.23	0.06	-	-	-	-
O_3:	73 ppb	0.24	0.15	0.08	0.06	1.6	0.02
S #1	4.5 μg m^{-3}	4.0	0.41	0.43	4.0	0.42	0.42
S #2	4.5 μg m^{-3}	0.50	0.19	0.25	0.45	0.20	0.22

obtained at the two experiments.) Although the conditions from run to run in each data set were superficially constant, some effects of nonstationarity undoubtedly exist. For example, the values of $a = \sigma_{\overline{w's}}/F_c$ for s = Q + χ are rather large in Table 4. The values of a = 0.20 and 0.23 are approximately twice those predicted by Equation (5b), and this corresponds to a numerical coefficient of nearly 50 rather than 12 in that equation.

To isolate the effects of sensor noise, statistics for $\overline{w'Q'}$ are used to remove the effects of natural variability. That is, we assume than an "ideal" standard deviation σ_i of concentration fluctuations is

$$\sigma_i = \sigma_Q \overline{w's'}/\overline{w'Q'}, \qquad (21)$$

and that the ideal value a_i for each chemical species is equal to the a found for water vapor flux. This implies that turbulence for Q in flux carrying eddies is inherently similar to that for the other species. Such a similarity for O_3 has been shown empirically (Wesely, 1983), but remains an unproven premise for the other chemical species. With σ_i and a_i determined, it is possible to compute the noise contributions to standard deviations as

$$\sigma_\chi = (\sigma_s^2 - \sigma_i^2)^{1/2} \qquad (22)$$

and to precision as

$$a_\chi = (a_s^2 - a_i^2)^{1/2}. \qquad (23)$$

Then, $\sigma_{\overline{w'\chi'}}$ is found as $a_\chi \overline{w's'}$ and the value of n* with only noise is found as $T^{-1}\sigma_w^2\sigma_\chi^2/\sigma^2_{\overline{w'\chi'}}$. Also, Table 4 shows values of the normalized frequency $f^* = n^*z/\bar{u}$ and the precision for the deposition velocity computed as σ_d (for v_d) equal to $\sigma_{\overline{w's'}}/\bar{s}$ or $\sigma_{\overline{w'c'}}/\bar{c}$. This deposition velocity parameter is presented only as a means of comparison facilitated by normalizing by dividing by mean concentration.

Each sensor has its own particular characteristics concerning run-to-run variability, as indicated by variations in the values of $|a|$, f^*, and σ_d. Results from two different types of ozone sensors are shown in Table 4, one relying on chemiluminescent reaction with NO (Table 1) and one relying on chemiluminescent reaction with C_2H_4 (DDIE), but in both cases the run-to-run variability is acceptably small. It appears that sensor noise limits precision to near 0.10 for one 25 min run. If the natural variability limits $|a|$ to 0.10 also, the vector sum would be 0.14 and only twice as many 25 min runs would be necessary to achieve the same precision in ozone flux estimates as would be obtained with a perfect sensor. Indeed, it has been possible to achieve estimates of ozone v_d to less than 0.01 cm s^{-1} in some cases (Wesely et al., 1981).

The results for NO_x and particulate sulfur with sensor #1 are considerably less encouraging than for O_3 eddy flux measurements. The noise in the two sensors is such that 5-20 half hours of data are needed to achieve precisions comparable to that for ozone fluxes. We have made the tacit assumption that the excessive variability is due entirely to sensor inadequacies, which might not be true if processes affecting NO_x and S uptake at the underlying surfaces actually cause such extraordinary variability. However, one only needs to compare the results in Table 4 from the two sulfur sensors in order to

be convinced that sensor limitations are extremely important. The malfunctioning particle sensor that produced the signal u clearly represents an extreme in poor sensor performance.

A question remaining to be addressed explicitly is whether run-to-run variability for noisy sensors can be estimated on the basis of data from only one run. From Equations (9) and (10), the run-to-run variability might be approximated as

$$\sigma_{\overline{w's'}} = \sigma_w \sigma_s (f^* \bar{T}u/z)^{-1/2}. \qquad (24)$$

With ideal sensor, f^* should be approximately equal to 0.5, which corresponds to $(1 - R_{ws}^2 + b^2)^{-1}$ from Equation (11b) and $(25R_{wc}^2)^{-1}$ or $(12R_{wc}^2)^{-1}$ from Equation (5) as evaluated with $b = 1$ and typical values of R_{wc}. Values of f^* for $c = 0$ in Table 4 are considerably smaller than 0.5, near 0.08, which indicates that excessive temporal variations in surface and atmospheric conditions increased $\sigma_{\overline{w'c'}}$ considerably. The values of f^* under "noise" in Table 4 range from 0.15 to 3.6 and can be used empirically to determine a minimum value of $|a|$ for a given sensor, provided a single half hour estimate of σ_x is accurate (i.e., the sensor characteristics are unchanging) and estimates of σ_w are available. Of course, σ_x might be assumed equal to σ_s if noise strongly dominates the signal. In general, for sensors that have a large amount of white noise, it would be desirable to filter out the signal fluctuations electronically at frequencies greater than $nz/\bar{u} \approx 2$ in order to reduce variability (provided substantial phase shifts are not introduced at the lower frequencies). If not, a value of $f^* \approx 3$ is appropriate in Equation (19), as is evident for some cases in Table 4.

CONCLUSIONS

The run-to-run variability of estimates of mass fluxes measured by eddy correlation can be strongly affected by sensor noise. Random noise will not bias the flux estimates systematically. Natural geophysical variability will cause a precision, expressed as $\sigma_{\overline{w'c'}}/F_c$ to have minimum values of 0.10 to 0.20 for half hour runs at a height of 5–10 m in moderate winds. The performance of current ozone sensors is largely satisfactory because only a slight amount of variability is added due to sensor noise, less than doubling the number of runs in order to reduce variability to its natural lower limit. Use of the sulfur and NO_x sensors considered here, however, requires 5–20 times the number of runs or length of total averaging time. In general, the variability is proportional to the value of σ_s from noisy sensors, and is inversely proportional to the square root of the averaging time needed.

It is evident that the technology used for fast response measurement of atmospheric trace constituents poses a major limitation to the application of eddy correlation to measure air-surface exchange rates. The development and employment of techniques that do not require fast response measurements should be continued. For man chemical species, nevertheless, eddy correlation has provided much of the knowledge now available on exchange processes that occur in the field and can provide a standard for comparison of fluxes estimated by alternate techniques.

Acknowledgements

Much of the data used in this paper was collected and analyzed with the assistance of Mr. David Cook of Argonne National Laboratory. Although the research described in this article has been funded wholly or in part by the U. S. Environmental Protection Agency (EPA) through IAG DW930060-01-0 to the U. S. Department of Energy, it has not been subjected to EPA review and therefore does not necessarily reflect the views of EPA and no official endorsement should be inferred.

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